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Stability Analysis of a Three-phase Converter Controlled DC Motor Drive

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***Abstract*—The design of the speed controller is important from the point of view of imparting desired transient and steady-state characteristic to the two quadrant converter controlled separately excited dc motor drive system. The poor design of the controller causes in losses and inefficient operation of the drive. Although many improved PI/PID design methods are proposed, such as root locus, Ziegler-Nichols (Z-N) methods etc., but they have shortcomings such as long testing time and limited control performance.To overcome this difficulty, we make use the theory of D-partition technique. Based on analytically characterizing the D-partition boundaries of the controller parameter space, necessary conditions of the maximum degree of stability are derived.The design of the controller and analysis of a converter controlled closed-loop dc motor drive is presented in this paper work. The effect of different factors like the time constant of proportional speed controller and the motor time constant on drive performance is analyzed. The D-partition technique is used to investigate the interaction of proportional speed time constant, amplifier gain and armature time constant on the stability of two quadrant converter-controlled closed loop separately excited dc motor drive. In this paper work, a procedure has been suggested to find the optimum value of the amplifier gain to give minimum settling time, which is the most important requirement of high performance drives or high fidelity drives. Using the D-partition technique, a comprehensive performance analysis of system design is carried out in this paper, using MATLAB environment.**

***Keywords*—Stability; Controlled dc motor drive; D-partition technique; MATLAB.**

I. INTRODUCTION

Electric motors convert electrical to mechanical energy. They play an important role as electromechanical energy converters in very significant manufacturing operations: transportation, material handling and most production processes. The ease of controlling these motors provides a significant property that can be taken advantage of meeting ever-increasing user demands that include the need for flexibility and precision, which is often the result of advances in technology within industry. Also, the need for energy conservation in order to safe-guard the environment is a key driver for improved efficiency in the employment of variable speed electric drives [1], [2].

The DC motor is widely used due to its simplicity in construction and the ease with which it can be controlled. For these reasons, in the 1970s, the DC variable speed drives were the preferred choice for industrial applications [3]. Nowadays, although the AC machines are almost entirely the preferred choice, the DC machines are still valued for their wide speed and torque range and also their overall efficiency. The DC motor has a wide application range that includes machine tools, traction hoisting, and robotics, etc. The rapid advancements in power electronics and control strategies further enhanced the overall applications of conventional DC motors. The mechanical commutation process within the DC motor, which enables the flow of current in one direction within its current carrying conductors, pose some limitations to the functioning of the conventional DC machine. The results of this are a cap on the maximum possible ratings on the DC motors and also the development of design strategies that focus on ways to avoid the employment of commutators and its associated components in future DC machine designs. The commutators are prone to frequent failures, which could be responsible for the breakdown of the equipment.

II. TUNING OF THE CONTROLLER

Generally, the efficient operation of variable speed electric drives are largely governed by controllers - the more efficient the controller, the more effective the drive will be in carrying out its assigned function. Closed loop control of electric drives hasnot always been available and accepted for industrial applications. In the 1950s, thecontrol of drives was normally open-loop and as a result motor speed was affected bychanges of load. This meant that there was a limitation in the possible speed rangebecause at low speeds, the motor would stall when the load was applied. But, by thelate 1950s, the closed loop control of variable speed drives had gained wide industryacceptance, especially because of its proposed benefits of greater accuracy and fasterresponse of variable speed drive systems, wider speed range of operation, ability totune the drive system to suit the application, etc [4].

Within the modern day closed loop control system for variable speed drives, there exists an inner-current loop control and an outer-speed loop control [3]. Conventional controllers based on the Proportional, Integral and Derivative (PID) family are often the preferred choice for implementing the control of drives and they have served the industrial drives for decades. This is mainly because of their simple control structure, ease of design, low cost and because they sufficiently satisfy the requirements of many industrial applications [5], [6].The actual tuning of a PID controller requires a good model (an abstraction of the real system) and certain design rules for its successful

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implementation. The tuning procedure can sometimes be a time-consuming and difficult task, above all, for complex plants. Some control engineers may take one to three days searching for a practically valid PID controller setting for certain industrial applications [5-7]. Furthermore, it is also realized that many PID controllers for closed loop systems are poorly tuned. This could be due to the fact that the design is based upon approximations of the actual system dynamics - a model. A poorly tuned control system may waste energy and cause excessive and unnecessary wear of the plants within the closed loop control system. Although many improved PI/PID design methods are proposed, such as root locus, Ziegler-Nichols (Z-N) methods etc, they have shortcomings such as long testing time and limited control performance [5].

The D-partition technique has been used in number of processes such as tuning PID controller parameters for first-order plus dead-time processes with the objective of maximizing the degree of stability. Since the presence of dead-time in a feedback loop gives rise to an infinite-dimensional closed-loop system, which hay an infinite number of poles and thus the conventional Routh-Hurwitz algebraic criterion of stability cannot be applied to characterize the necessary conditions of the maximum degree of stability. To overcome this difficulty, we make use the theory of D-partition technique. Based on analytically characterizing the D-partition boundaries of the controller parameter space, necessary conditions of the maximum degree of stability are derived [8]. With these derived conditions, the problem of maximizing the degree of stability is converted to a set of parametric optimization problems, whose solutions can be obtained by an existing method [9]. Also the effect of variation of the other parameters of the drive can also be studied with this technique. To the best of the information available to the author, performance and stability analysis of Converter-Controlled closed-loop dc motor drive, using D-partition technique, has not been carried so far. The parameter plane technique is proposed to study the stability of such drive and design carried out for fastest transient response. A comprehensive analysis of system design is presented, which shows that the value of PI controller time constant influence the value of PI controller gain for minimum settling time.

The D-partition technique has also been used in number of processes [10], [11]. The work related to the performance and stability analysis of indirect vector-controlled close-loop drive and Permanent Magnet Synchronous Motor (PMSM) drive using the same technique has been explored by the same author [12], [13].

III. Description of DC Motor Drive

The control schematic of a two-quadrant converter-controlled separately-excited dc motor drive is shown in figure1. The motor drive is a speed controlled system. The thyristor bridge gets its ac supply through a three-phase transformer and fast acting ac contactors. The dc output is fed to the armature of the dc motor.

The field is separately excited and the field supply can be kept constant or regulated depending upon the need for the field weakening mode of operation. The motor has a taco-generator whose output is utilized for closing the speed loop. The motor is driving a load considered to frictional for this treatment. The output of the tachometer is filtered to remove the ripples to provide the signal ω_{mr}. The speed command ω_r^* is compared to the speed signal to produce a speed error signal. This signal is processed through a proportional-plus-integral (PI) controller to determine the torque command. The torque command is limited to keep it within the safe current limits and the current command is obtained by proper scaling. The armature current command is obtained by proper scaling. The armature current command i_a^* is compared to the actual armature current i_a to have a zero current error. In case there is an error, a PI current controller processes it to alter the control signal v_c. The control signal accordingly modifies the triggering angle α to be sent to the converter for implementation.

The inner current loop assures a fast current response and hence also limits the current to a safe preset level. This inner current loop makes the converter a linear current amplifier. The outer speed loop ensures that the actual speed is always equal to the commanded speed and that any transient is overcome within the short feasible time without exceeding the motor and converter capability.

The design of the gain and time constant of the speed and current controllers is of paramount importance in meeting the dynamic specifications of the motor drive. The dynamic designs are considered in the next section [14].

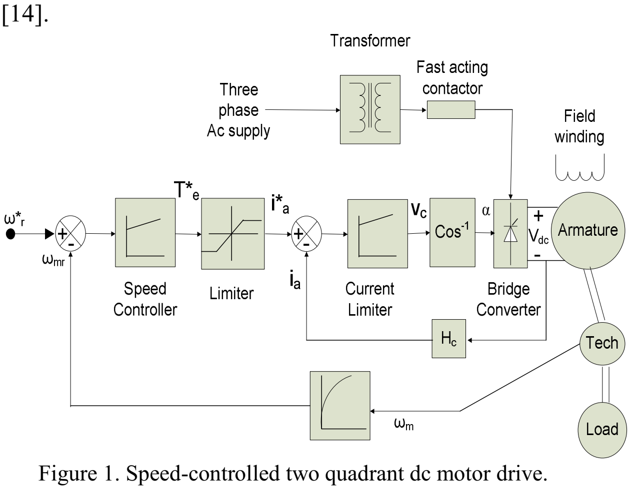

Figure 1. Speed-controlled two quadrant dc motor drive.

IV. Block Diagram Derivation And Evaluation Of Transfer Function

The Block diagram of vector-controlled PM synchronous motor is derived in this section. This is made possible by deriving the transfer functions of the various operating systems such as the dc motor, inverter, speed controller and feedback transfer functions. By combining the subsystem block diagrams, the final block diagram of the induction motor drive is assembled.

A. Derivation Of Transfer Function of Subsystems:

a) DC Motor and Load:

The dc machine closed loop controlled drive has an inner current loop and outer speed loop. These loops are magnetically coupled. To decouple the inner current loop from the machine-inherent induced emf loop it is necessary to split the transfer function between the speed and voltage into two cascade transfer functions first between speed and armature current and then between armature current and input voltage, represented as

$$\frac{\omega_m(s)}{V_a(s)} = \frac{\omega_m(s)}{I_a(s)} \cdot \frac{I_a(s)}{V_a(s)} \tag{1}$$

where,

$$T_m = \frac{J}{B_t}, B_t = B_1 + B_l$$

$$\frac{\omega_m(s)}{I_a(s)} = \frac{K_b}{B_t(1+sT_m)} \tag{2}$$

and

$$T_m = \frac{J}{B_t}, B_t = B_1 + B_l$$

b) Transfer Function of the Converter:

The converter after linearization is represented by

$$G_r(s) = \frac{K_r}{1+sT_r} \tag{3}$$

where,

$$K_r = 1.35\frac{V}{V_{cm}}, V/V ,$$

$$T_r = \frac{1}{12 f_s}, s$$

c) Speed Controller:

The transfer function of current and speed controller is given

$$G_c(s) = \frac{K_c(1+sT_c)}{sT_c} \tag{4}$$

$$G_s(s) = \frac{K_s(1+sT_s)}{sT_s} \tag{5}$$

d) Current Feedback Transfer Function:

The current feedback signal function has only gain block whose value is given by

$$G_c(s) = H_c \tag{6}$$

e) Speed feedback Transfer Function:

The speed feedback signal is processed through a first order filter whose transfer function is given by

$$G_w(s) = \frac{\omega_{rm}(s)}{\omega_r(s)} = \frac{K_w}{1+sT_w} \tag{7}$$

B. Block Diagram of Two-Quadrant Converter-Controlled PMSM Drive:

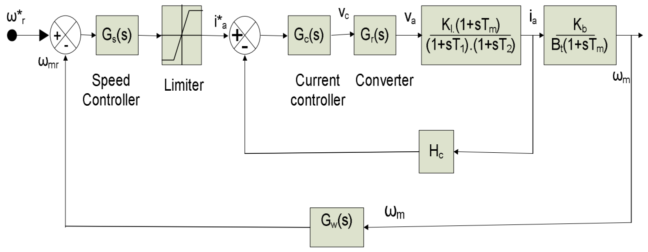

Figure 2. Block diagram of dc motor drive.

Solving the block diagram of the system shown in figure 2, the open loop transfer function G(s) is given by

$$G(s) = \frac{K_s K_a K_c K_r K_b [1 + s(T_s + T_c) + s^2 T_s T_c]}{s^2 T_s T_c B_t [T_r T_a T_m s^3 + (T_r T_a + T_a T_m + T_r T_m)s^2 + (T_a + T_m)s + (1 + sT_r)(1+K)]} \tag{8}$$

The closed loop transfer function is given by

$$\frac{G(s)}{1+G(s)H(s)} = \frac{K_s K_a K_c K_r K_b (1 + a_1 s + a_2 s^2 + a_3 s^3)}{A_1 s^6 + A_2 s^5 + A_3 s^4 + A_4 s^3 + A_5 s^2 + K(1 + b_1 s + b_2 s^2)} \tag{9}$$

From the equation (9), the characteristic equation of the closed loop system can be written as

$$1 + G(s)H(s) =$$

$$A_1 s^6 + A_2 s^5 + A_3 s^4 + A_4 s^3 + A_5 s^2 + K(1 + b_1 s + b_2 s^2) = 0 \tag{10}$$

where,

$$A_1 = T_s T_c T_m T_a T_r T_w B_t$$

$$A_2 = T_s T_c B_t [T_r T_a T_m + T_w (T_r T_a + T_a T_m + T_r T_m)]$$

$$A_3 = T_s T_c B_t [T_r T_a + T_a T_m + T_r T_m + T_w (T_a + T_m) + T_w (1+K) T_r]$$

$$A_4 = T_s T_c B_t [T_a + T_m + (T_r + T_w)(1+K)]$$

$$A_5 = T_s T_c B_t (1+K)$$

$$K = K_c K_s K_b K_a K_r H_w$$

$$a_1 = T_s + T_c + T_w$$

$$a_2 = T_s T_w + T_w T_c + T_s T_w$$

$$a_3 = T_s T_c T_w$$

$$b_1 = T_s + T_c$$

$$b_2 = T_s T_c$$

$$K_a = \frac{1}{R_a}, T_a = \frac{L_a}{R_a}, T_m = \frac{J}{B_t},$$

V. Drive Specifications

To illustrate the analysis, the drive represented by figure 2, with the following specifications is considered:
220V, 8.3 A, 1470 rpm,
Armature winding resistance, $R_a = 4\Omega$,
Armature winding inductances, $L_a = 0.072$H,
Moment of inertia of motor and load, J = 0.0607 $Kg.m^2$.
Viscous friction coefficient, $B_t = 0.0869$ N m s/rad
Gain of the tachometer, $H_w = 0.065$,
Time constant of the tachometer, $T_w =$ 0.002 sec,
Gain of the converter, $K_r = 31.05$ V/V,
Time constant of the converter, $T_r = 0.00138$ sec,
Gain of the PI current-controller, $K_c = 2.33$,
Time constant of the PI current-controller, T_c = 0.0208 sec,
Gain of the PI speed-controller, $K_s = 28.73$,
Time constant of the PI speed-controller, $T_s = 0.0188$ sec,
Gain of the current feedback loop, $H_c = 0.355$ V/A.

VI. Use of Parameter Plane Technique

The parameter plane technique is used to study the effect of system parameters on the drive stability and determine the value of amplifier gain for minimum settling time.Now we have to select the parameters of interest [15, 16].

A. *Effect of Variation of System Parameters on Dynamic Stability:*

The parameter plane technique also known as the D-partition technique, can be used for studying effect of variation of system parameters, considering two of them at a time. In the case under study, there are three important parameters of the interest T_a, $T_s$and gain K .The study aims at determining the suitable values of gain K and motor armature time constant T_a for known values of PI controller time constant T_s. Therefore the dynamic stability has been studied for variations in these three parameters in the following two combinations:

(a) T_a and K varied; T_s kept constant.
(b) T_s and K varied; T_a kept constant.

B. *Variation of Armature Time Constant T_a and Gain K:*

In this case the parameters of interest are time constant T_a and gain K. From equation (9), the characteristic equation is given by,

$$T_a(K_1 s^5 + K_2 s^4 + K_3 s^3 + K_4 s^2) + K(1 + b_1 s) + L_1 s^4 + L_2 s^3 + L_3 s^2 + L_4 s = 0 \quad (11)$$

where,

$$K_1 = T_s T_c B_t T_m T_r T_w$$
$$K_2 = T_s T_c B_t (T_w T_m + T_w T_r + T_r T_m)$$
$$K_3 = T_s T_c B_t (T_r + T_m + T_w)$$
$$K_4 = T_s T_c B_t$$
$$L_1 = B_t T_s T_c T_m T_r T_w$$
$$L_2 = B_t T_s T_c (T_r T_m + T_w T_m + T_r T_w)$$
$$L_3 = B_t T_s T_c [T_m + (T_r + T_w)(1 + K_1)]$$
$$L_4 = B_t T_s T_c [K_1 + 1] \quad (12)$$

Substituting s = jω in equation (11) and solving for T_a and K,

$$T_a = (S_1.Q_2 - S_2.Q_1) / \Delta_1 ,$$

$$K = (P_1.S_2 - P_2.S_1) / \Delta_1 \quad (13)$$

where,

$$P_1 = 6.6033*10^{-11}*\omega^6 + 2.3902*\omega^4;$$
$$P_2 = 8.0685*10^{-8}*\omega^5 - 3.398*10^{-5}*\omega^3;$$
$$Q_1 = 1 - 3.91*10^{-4}*\omega^2;$$
$$Q_2 = 0.0396*\omega;$$
$$S_1 = -8.1115*10^{-8}*\omega^4 + 1.892*10^{-4}*\omega^2;$$
$$S_2 = -6.6033*10^{-11}*\omega^5 + 2.4428*10^{-5}*\omega^3;$$
$$\Delta_1 = P_1.Q_2 - P_2.Q_1; \quad (14)$$

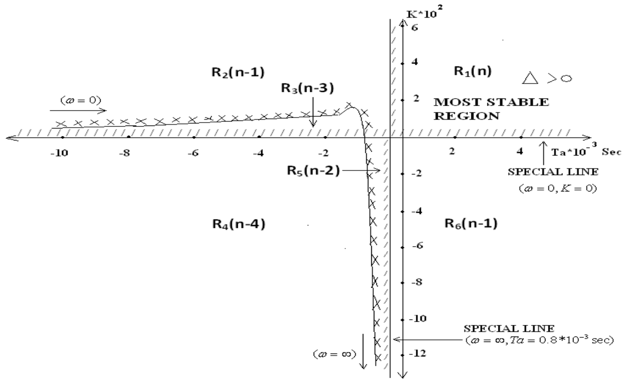

Figure 3. D-partition curve for the linear case in T_a-K plane.

From equation (13),the D-partition boundary in the (T_a-K) plane can be plotted as shown in figure 3. Following the Neimark hatching rule [7],the region of stability is determined. The entire (T_a-K) plane is divided into regions marked R_1,R_2,R_3………R_6,and the number within the parenthesis denotes the relative number of roots present in the left half of S-plane. The most stable regions are R_1,which corresponds to maximum number of roots (n). The most stable region is therefore the region R_1.This reveals that any combination of positive values of T_a and K from regionR_1, will lead to the stable operation.

C. Variation of Controller Time Constant T_s and Gain K

In this case, the parameters of interest selected are time constant of PI controller T_s and overall gain K. From the equation (9) the value of characteristic equation in terms of these parameters is given by

$$1+G(s)H(s)=$$
$$(M_1 s^5 + M_2 s^4 + M_3 s^3 + M_4 s^2 + M_5 s + K(sN+1) + KT_s(Ns^2+s) = 0 \quad (15)$$

where,

$$M_1 = T_c B_t T_m T_a T_r T_w$$
$$M_2 = T_c B_t [T_r T_a T_m + T_w (T_r T_a + T_a T_m + T_r T_m)]$$
$$M_3 = T_c B_t [T_m T_a + T_r T_m + T_a T_r + T_w (T_a + T_m) + T_w (1+K_1) T_r]$$
$$M_4 = T_c B_t [T_a + T_m + (T_r + T_w)(1+K_1)]$$
$$M_5 = T_c B_t (K_1 + 1)$$
$$N = T_c \quad \ldots\ldots (16)$$

It may be noted here that the parameters of interest, in this case do not occur linearly in the characteristic equation (9). Substituting s = jω and separating the real and imaginary parts, the corresponding system of two simultaneous equations can also be written as

$$H_1 * T_s * K + G_1 * T_s + E_1 * K + D_1 = 0,$$
$$H_2 * T_s * K + G_2 * T_s + E_2 * K + D_2 = 0, \quad (17)$$

These two equations provide two independent sets of values of controller time constant and gain obtained as (T_s, K) and (T_s', K') as

$$T_s = \{-e + (e^2 - 4*a*c)^{1/2}\}/2*a;$$
$$K = -(G_1 * T_{in} + D_1)/(H_1 * T_s + E_1);$$
$$T_s' = \{-e - (e^2 - 4*a*c)^{1/2}\}/2*a;$$
$$K' = -(G_1 * T_{in}' + D_1)/(H_1 * T_s' + E_1); \quad (18)$$

where,

$$a = G_2 * H_1 - G_1 * H_2;$$
$$b = E_2 * H_1 - E_1 * H_2;$$
$$c = E_1 * D_2 - E_2 * D_1;$$
$$e = G_2 * E_1 - G_1 * E_2 + H_1 * D_2 - H_2 * D_1;$$
$$J = -a * T_{in} + b * K + G_1 * E_2 - G_2 * E_1;$$

$$H_1 = -2.08*10^{-2} * \omega^2;$$
$$H_2 = \omega;$$
$$G_1 = 6.3223*10^{-11} * \omega^6 + 2.7178*10^{-5} * \omega^4 - 2.3*10^{-3} * \omega^2;$$
$$G_2 = 8.076*10^{-8} * \omega^5 - 1.3*10^{-3} * \omega^3;$$
$$E_1 = 1;$$
$$E_2 = 2.08*10^{-2} * \omega;$$
$$D_1 = 0;$$
$$D_2 = 0; \quad \ldots\ldots (19)$$

From equation (18), the D-partition boundary in the T_s-K plane can again be plotted. It is shown in the fig. 4. Following the Neimark hatching rule, the region of stability is determined. The entire T_s-K plane is divided into regions marked R_1, R_2,………R_6, and the number within parenthesis denotes the relative number of roots present in the left half of s-plane. The most stable region is R_1 and R_5, which correspond to maximum number of roots (n).

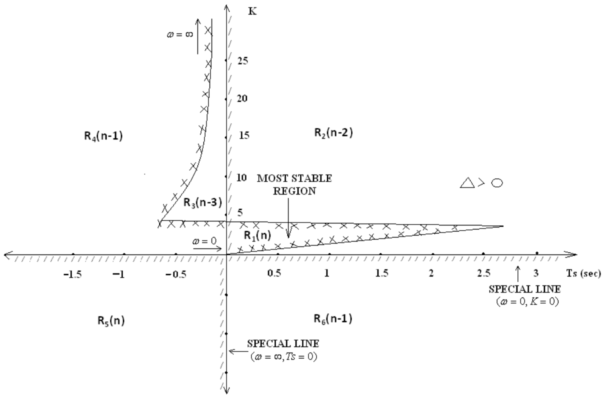

Figure 4. D-partition curve for the nonlinear case in T_s-K plane.

As the region R_5, corresponds to the negative values of K and it is not a feasible region. The most stable region is therefore the region R_1. It is again observed that any combination of the positive values of T_s and K can be selected to provide the most stable operation.

VII. Design of the Drive System for Maximum Stability with Minimum Settling Time

From the most stable region of figure 4, a number of values of gain K can be selected for a given value of controller time constant T_s. Out of these values of K, a particular value that gives the minimum settling time and hence the fastest transient response may be determined. This value of K has been determined as explained below. Substituting s = (-σ + j ω) in the characteristic equation (15), a set of different D-partition boundaries can be obtained for different increasing positive values σ. In each case, the most stable region can be determined as before. The larger the value of σ, narrower is the most stable region, and there exist a maximum value of σ beyond which the most stable region disappears. This critical value of σ is called σ_c. The D-partition boundary for σ = σ_c can be plotted and the mast stable region marked. A value of gain K corresponding to a given value of T_s selected from this region will give the minimum settling time. It can therefore be inferred that the value of gain K is directly influenced by time constant T_s if the system is designed for minimum settling time.

For the case under study, the value of σ_c is obtained as 71.1, for which the D-partition boundary is plotted as shown in figure 5. The most stable region is R_1 containing a maximum number of roots in the left half of s-plane. From this region, the value of gain K is obtained corresponding to a given values of T_s.

From the most stable region R_1, it can be noted that for the given value of T_s = 0.0188 sec, the corresponding value of the gain K, selected from the most stable region is 105.Knowing the value of K, the value of the controller gain for the given value of PI controller time constant T_s, can be calculated as K_s = 70.8839from the following relation:

$$K_s = K / (H_w*K_a*K_c*K_r*K_b)$$

From this observation we can infer that if we have to design the PI controller for maximum stability and minimum settling time, the value of the gain K_s of the PI controller is 70.8839. As the D-partition technique indicates the relative stability of the system, the absolute stability is varied using Routh criteria.

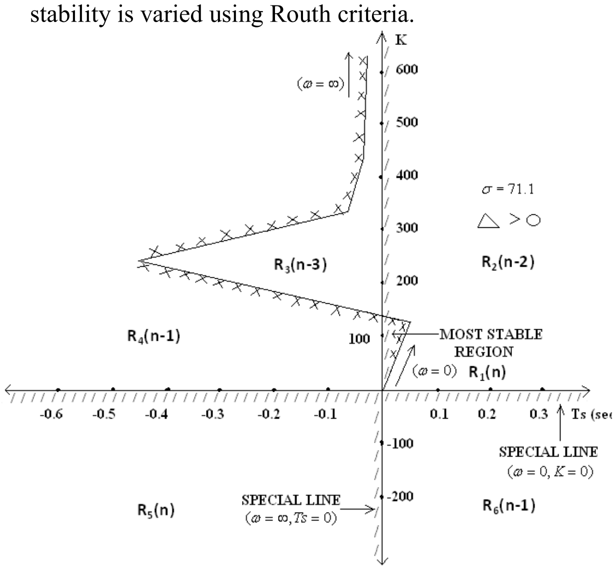

Figure 5. D-partition curve for the nonlinear case in T_s-K plane.

VIII. CONCLUSION

The work presented in this paper work deals with the stability analysis of a indirect vector controlled induction motor closed loop drive. The mathematical model of the above drive system has been developed.By using the same mathematical model, the transfer function as well as the characteristic equation of the drive system has been derived. The Parameter Plane Technique is used to investigate the effect of system parameters, like the gain and time constant of the PI controller, on the stability of the drive system.The analysis has been carried out for two different cases depending upon the parameters of interest selected:

a. Linear case

b. Non-linear case

For this case, the drive system is designed for minimum settling time.In the first case the parameters of interest selected are armature time constant T_{in} and the overall gain K of the system while in the last two cases, the parameters of interest selected are time constant of the PI controller T_s and overall gain K of the system. From the value of the overall gain K, the value of the controller gain K_s can be obtained. The range of the possible gain and time constant for fastest transient response can be computed from the D-partition boundary plot as discussed in the paper. Thus the proposed technique provides a handy tool for obtaining the correct system parameter for obtaining most stable operation of the drive system and a guide line for the design of high fidelity drives.

REFERENCES

[1] W. Leonhard, Control of Electrical Drives, *Springer*, *Berlin,* 2001.

[2] A. Hughes, Electric Motors and Drives, *Newnes, London*, 2007.

[3] P. C. Sen, C. S. Namuduri, and P. K. Nandam, "Evolution of control techniques for industrial drives," *IEEE International Conference on Power Electronics, Drives and Energy Systems*, New Delhi, India, vol. 2, pp. 879 – 875, 8-11 Jan, 1996.

[4] P. Shilston, "Development of industrial drives in the 1950s," *Engineering Science and Education Journal*, vol. 101, no. 2, pp.153 – 158, August 2001.

[5] Q. Bi, W-J. Cai, Q- G. Wang, C-C. Hang, E-L. Lee, Y. Sun, K-D. Liu, Y. Zhang, and B. Zou, "Advanced controller auto-tuning and its application in HVAC systems," *Control Engineering Practice, Elsevier*, vol. 8, no. 6, pp. 633 – 644, June 2000.

[6] Krakow K. I. and Lin S., "Pi control of fan speed to maintain constant discharge pressure," *ASHRAE Transactions*, vol. 101, no. 2, pp. 498 – 407, 1st Jan, 1995.

[7] M. J. Pinnella, E. Wechselberger, D. E. Hittle, and C. O. Pederson, "Self-tuning digital integral control," *ASHRAE Transactions*, vol. po-87-05, no.2, pp. 202–210, 1987.

[8] C. Hwang, S-H. Hwang, and J-F. Leu, "Tuning PID controllers for time-delay processes with maximizing the degree of stability" *5th Asian Control Conference*, Victoria, Australia, vol .1, pp. 466 - 471, 20-23 July, 2004.

[9] S. U. Ahmad, and N. Hasan, "Stability analysis of phase controlled closed loop drive with elastic coupling using D-partition technique" *Electric Power components and Systems (U.S.A.)*, vol. 44, no. 8, pp.819-842, 2005.

[10] J. Nanda, "Analysis of steady state stability of a two machine system by D-decomposition technique" *IEEE Trans. On Power Apparatus and Systems*, PAS-90, no. 4, pp. 1848-1855, July 1971.

[11] J. Nanda, "Optimisation of voltage regulator gains by the D-decomposition technique for best steady state stability" *IEEE Trans. On Power Apparatus and Systems*, PAS-90, no. 6, pp. 2488-2494, Nov. 1971.

[12] S. Islam, F. I. Bakhsh, M. Khursheed, and A. Iqbal, "Design and Performance Analysis of an Indirect Vector-Controlled Closed-loop Drive System using D-partition Technique." *IEEE International Conference on Process Automation, Control and Computing, (PACC-2011)*, Coimbatore, India, 20-22 July, 2011,.

[13] S. Islam, M. Khursheed, F. I. Bakhsh, S. U. Ahmad and A. Iqbal, "A Novel Technique for the Design of Controller of a Vector-Controlled Permanent Magnet Synchronous Motor Drive," *Annual IEEE India Conference (INDICON-2011)*, BITS Hyderabad, India, 16-18 Dec., 2011.

[14] R. Krishnan, Electric Motor Drives-Modeling Analysis and control, *Prentice Hall, U.S.A.,* 2001.

[15] M. V. Meerov, Introduction to the dynamics of automatic regulating of electrical machines, *Butterworth's (translated from Russian), London,* 1961.

[16] D. D. Siljak, Non-Linear System-The Parameter Analysis and Design, *John Wiley and Sons, New York,* 1969.